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Advances in Astrometry and Geophysics Made Possible by Radio Interferometry

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I. Introduction

One of the oldest problems in astronomy and life is "Where am I?" The fields of astrometry and geodesy come together to answer this question using the positions of solar system objects and stars, and in the last 300 years, clocks. Navigators using sextants accurate to an arcminute determine positions within a nautical mile on the Earth's surface. Careful measurements in the mid-20th Century pushed star position accuracies to 0.1 arcsecond, resulting in formal accuracies in terrestrial position of a few meters using astrolabes and transit circles. With the advent of space science in the 1960s, measurement of the Earth's gravitational potential, the Earth-Moon distance, etc., were made. New methods arose to meet the challenge to provide an increase in accuracy. Two methods proved to be particularly useful, laser ranging to the Moon and artificial Earth satellites and Very Long Baseline Interferometry (VLBI). This paper deals with the advances made by VLBI.

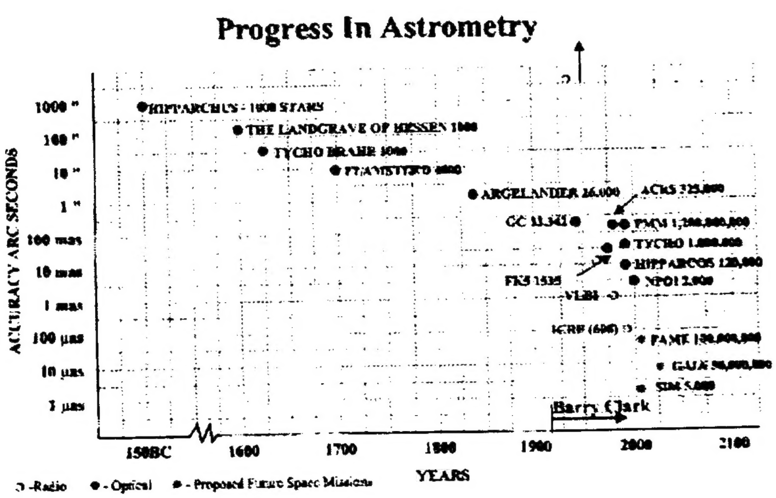

Figure 1. Progress in Astrometry.

Radio Interferometry has had a tremendous impact on the development of astrometry and geodesy. Barry Clark has played a leading role in developing the technology of radio interferometry through his work on connected-element interferometry, i.e., the Green Bank Interferometer and Very Large Array; and VLBI, i.e., the Mark I and II VLBI systems and the Very Long Baseline Array (VLBA). These efforts resulted in an increase in astrometric accuracy of four orders of magnitude. Stellar positions at radio wavelengths now can be measured with a precision of 0.1 milliarcseconds (mas). Earth orientation parameters such as UT1 and polar motion are now measured with precision's of 10 microarcseconds (µas). The precession constants and models for nutation need revision to precisions at the µas level. Tectonic plate motion was directly measured in the 1980s. These were and are exciting times for research in these fields and Barry's scientific career parallels them especially in astrometry, as shown in Figure 1.

II. Background

The astronomical reference system as taught in all elementary astronomy courses is the celestial system of right ascension and declination. This system was defined by a reference frame consisting of optically bright stars. It is only in the last seventy-five years that serious observations have been made at other than optical wavelengths. Radio observations matured quickly after World War II, and the entire electromagnetic spectrum was opened up with the beginning of the space age in the 1960s. If possible, a celestial reference frame should be based on objects that are fixed in space. A star's position in space is described by a position at a defined epoch, parallax, proper motion and radial velocity. The level of accuracy achieved with optical transit circles is about 0.1 arcsecond. A long series of observations will improve knowledge of the star's proper motion. Proper motions for bright stars were accurate at the level of about 3 mas before the Hipparcos spacecraft. All observations were made from the Earth's surface. In order to transform from an apparent position to a mean position and then to another epoch, knowledge of the Earth's precession, nutation, figure, etc., are needed. Separation of precession and nutation from the proper motions of stars proved difficult at levels below 1"/ century.

III. The Optical Reference System and Frame

The increase in astrometric accuracy achieved by radio interferometry has resulted in a new celestial reference system and frame. The previous system was defined by a frame made up of the optical positions of bright stars. Fundamental catalogs were compiled from catalogs of "absolute or fundamental" observations, i.e., the positions were on an instrumental system, the pole was determined independently and the zero point of right ascension was adjusted to a dynamical system using observations of the Sun and solar system objects. These fundamental catalogs, denoted as FK 3 (Kopff 1937), FK4 (Fricke & Kopff 1963) and FK5 (Fricke, Schwann & Lederle 1988), compiled by the Astronominischen Rechen Institut, first in Berlin and later in Heidelberg, used the positions of 925, and later 1535 stars in their initial catalogs to define the reference frame. These were well-studied stars, brighter then 8th visual magnitude. The precision of the FK5 catalog's positions and proper motions at average mean epoch 1950.0 was believed to be 20 mas and 0.8 mas/yr respectively. On later comparison of the FK5 frame with the Hipparcos frame at epoch 1991.25, regional distortions as large as 150 mas were found (Mignard & Froeschle, 1997).

The optical reference system defined by the Fundamental Catalogs has the following structures: an origin (barycenter of the solar system), a fundamental plane (celestial equator), and a zero point of the fundamental plane (vernal equinox, intersection of the mean equator and ecliptic). In defining this reference system with stars, their positions establish the reference frame defining the realization of the axes of the reference system. The reference system must have a reference epoch and specify all the necessary procedures and constants required to transform the frame from the reference epoch to any other date.

In the 1980s the FK5 system came into being with J2000 as the epoch. The FK5 system was improved over that of the FK4 by adopting the IAU 1976 value of precession (Lieske et al. 1977) and nutation (Seidelmann 1982), a new determination of the equinox and equator (Fricke 1982), a precessional correction determined from FK4 proper motion assuming a kinetic model of

parallactic motion and galactic rotation (Fricke 1981) and a new definition of time (Aoki et al. 1982).

IV. The Radio Reference Frame

At the beginning of Barry's astronomical career in the 1960s, positions determined by radio observations were accurate to about an arcsecond, and then quasars were discovered. Quasars, since they are extragalactic, were soon recognized as objects whose positions could be employed in a reference frame. Since the spatial structure of their emission was not known, VLBI was developed to answer the astrophysical questions about the energy mechanisms for these objects. Barry, together with other NRAO scientists and their world-wide collaborators, performed experiments in the late 1960s and found the spatial structure to be very compact, of order one mas. The next step, and the topic of this paper, is the astrometry of these objects. This quickly improved with the "long" baseline connected-element interferometers such as the Cambridge Array and the Green Bank Interferometer. In the 1970s the positions of compact extragalactic radio source were determined to 20 mas (Wade & Johnston 1977) with the 35 km baseline of the Green Bank Interferometer. This work paved the way for more precise geodetic measurements. The Navy began operation of the Green Bank Interferometer in 1978 for the determination of Earth orientation parameters. At the same time, VLBI was coming of age with astrometric positional accuracy that equaled that of the Green Bank Interferometer (Clark et al. 1976).

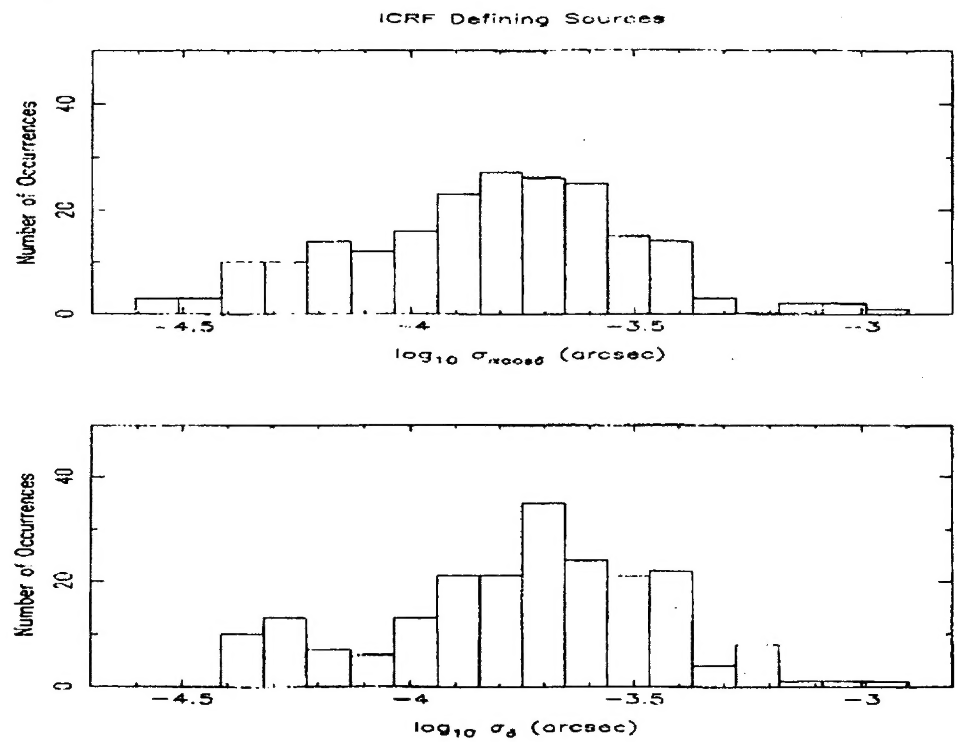

Figure 2. Formal errors in he positions of the 212 sources defining the ICRF. The mean position is below 100 μas.

In the 1980s, VLBI made major steps in its development through NASA's Crustal Dynamics Project. Various catalogs of radio source positions were published by Goddard Space Flight Center (GSFC), the Jet Propulsion Laboratory (JPL), the National Geodetic Survey (NGS), and

the Naval Research Laboratory/United States Naval Observatory (NRL/USNO). These catalogs were combined by the International Earth Rotation Service (IERS) beginning in the late 1980s to form the basis for a radio reference frame. A program to establish a global radio reference frame of 400 sources was undertaken in 1986 (Johnston et al. 1988). All sources would have optical counterparts. All available VLBI dual frequency bandwidth synthesis Mark III VLBI data from geodetic, Earth orientation and astrometric programs obtained between 1979 and 1993 were used to solve for a catalog of positions from first principles in a single solution (Johnston et al. 1995). The dataset consisted of 1,015,292 pairs of group delay and phase delay rate observations. A catalog of 436 sources, all with accuracies smaller than 3 mas in each coordinate and 211 with accuracies smaller than 1 mas, was produced to define the radio/optical reference frame at a frequency of 8.4 GHz.

V. The ICRS and ICRF

The IAU at the XXI General Assembly in 1991 decided that the celestial reference system should be based on a set of distant extragalactic objects. A list of suitable candidate sources to define this reference frame was adopted at the XXII General Assembly in 1994. At the XXIII General Assembly in 1997, the IAU adopted a new reference system based on a reference frame defined by extragalactic radio sources. This system, adopted on January 1, 1998, is known as the International Celestial Reference System (ICRS) and is specified in the 1991 IAU resolutions. The origin is located at the solar system barycenter via modeling of VLBI observations in the framework of General Relativity. The motion of the pole is defined by the conventional IAU models for precession (Lieske et al. 1977) and nutation (Seidelmann 1982) and the origin of right ascension is defined by fixing the right ascension of 3C273's (Hazard et al. 1971) FK5 value transferred to J2000.0.

An IAU Working Group on Reference Frames produced the catalog (Ma et al. 1998) defining the International Celestial Reference Frame (ICRF) from 1.6 million pairs of group and phase delay rate data obtained between August 1979 and July 1995. The ICRF consists of 212 defining extragalactic radio sources. These sources have positional errors less than 1 mas. Figure 2 displays the formal errors of these positions. The reported positions in the catalog were derived by multiplying the formal

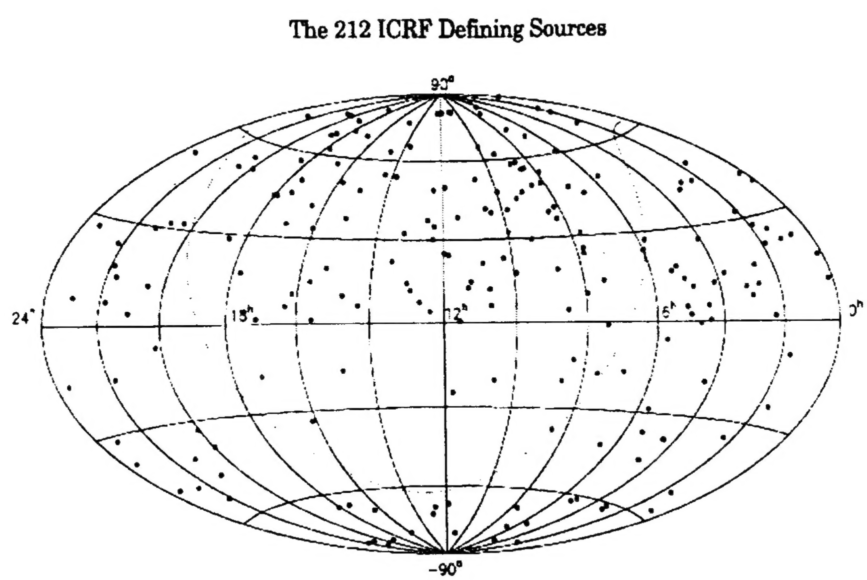

Figure 3. The location of 212 sources defining the International Celestial Reference Frame. Note that the majority are in the Northern Hemisphere.

errors by 1.5 and adding this in quadrature with 250 mas. Formal errors are typically < 100 μas which is the precision of these positions. Typically those sources with the lowest errors have been observed over several years. The geodetic experiments contributed most of the observations of these sources.

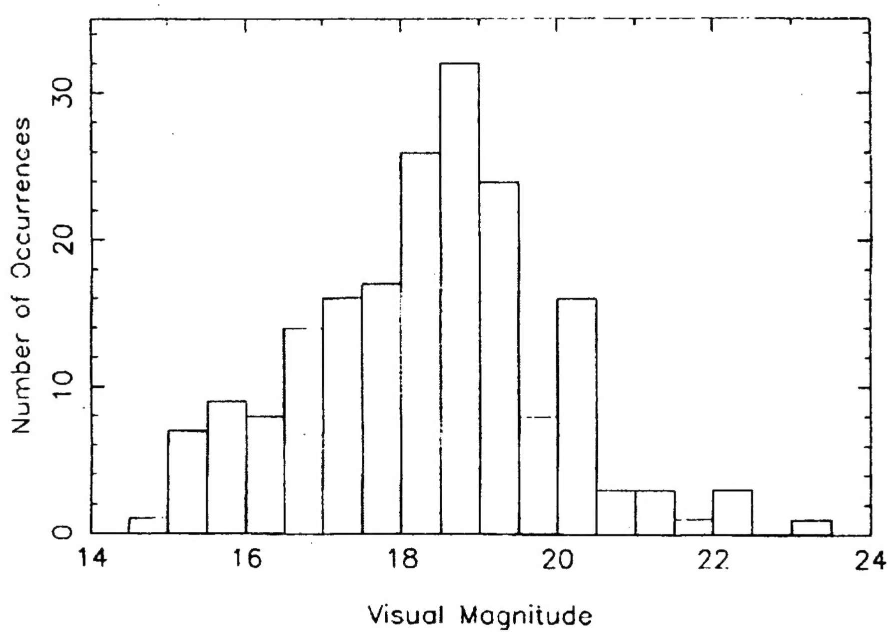

Figure 4. The visual magnitude of the optical counterparts of the ICRF sources. Note that they are much fainter than the Hipparcos stars and peak between 18th and 19th visual magnitude. Thus, bright stars with radio counterparts were used to link the radio ICRF and optical Hipparcos frames.

Figure 3 displays the distribution of these sources on an Aitoff equal area projection. To establish a defining source a long series of observations are necessary. Only 22 percent of the defining sources are in the southern hemisphere due to a lack of observations. An additional 294 candidate sources that may become defining sources with future observation also are given in the catalog. There are also 102 "other" sources whose positions may show variations with time or whose positions are less well known. The visual magnitudes of the defining sources are presented in Figure 4. This is seen to peak between 18th and 19th visual magnitude.

The geodetic data, which, by far, forms the majority of data in the data base used to generate the ICRF, was obtained over a limited number of hour angles, usually with a small number of antennas, and is limited in its ability to produce a map of the radio emission from these sources. Observations with the VLBA of these sources may be found on Radio Reference Frame Image Data Base (RRFID) maintained by Alan Fey (http://maia.usno.navy.mil/rorf/rrfid.html). This website, as well as Fey & Charlot (1997), also details the effect of source structure on the precise positions of these defining sources. A source index is given to estimate the astrometric quality of the sources. This is presented in Figure 5. An index of 1 is very good, 2 is good, 3 marginal and 4 not usable. The structure of the radio emission at 8.4 GHz is also shown in Figure 5.

Future observations with the VLBA and other VLBI arrays, especially those in the southern hemisphere, are needed to maintain and extend the ICRF. Variations in source structure will cause defining sources to be downgraded to candidate sources and candidate sources to become

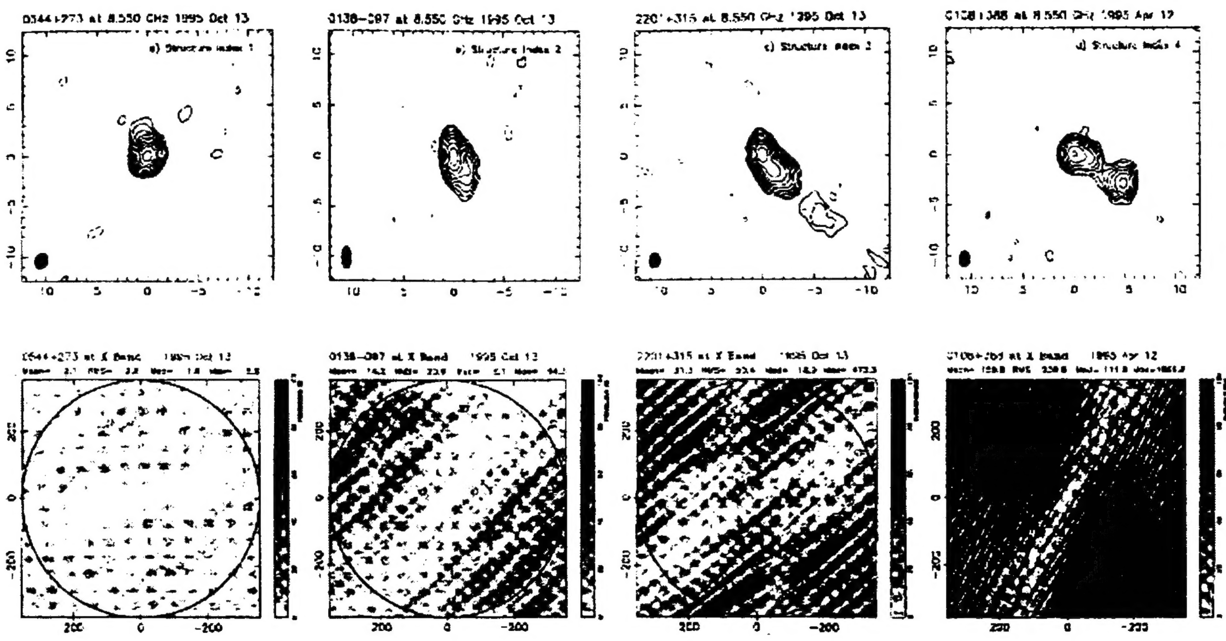

Figure 5. The source index at 8.4 GHz for the quality of extragalactic radio sources for astrometric applications, especially applied to sources for the ICRF. Note that sources with an index of 1 (left) are excellent, while those with an index of 4 (right) are unusable. This can be seen easily by a study of their spatial structure (top) and delay (bottom).

defining sources. The ICRF should be looked upon as evolving with time. The ICRF will have an epoch with the defining sources and their positions being defined at that epoch. This is necessary, as the variations in spatial structure will cause variations in position. Since the spatial emission is often in the form of "jets," these sources may display apparent proper motions. A large number of observations will be required to maintain the ICRF. At present, the accuracy of the ICRF is also determined by our lack of knowledge of systematic errors in models as well as errors contributed by the atmosphere. It should be possible to improve our understanding of nutation, the atmosphere, and other error contributing effects, resulting in a positional accuracy of less than 50 μas. Again a large number of observations are needed to achieve this. The VLBA can make a very significant contribution in achieving this.

VI. The Hipparcos Space Mission

The major limitation to optical astrometry from the Earth's surface is the errors introduced by the atmosphere. To overcome this, the Hipparcos space mission produced a global astrometric catalog of 118,217 stars. The optical magnitudes of these stars are brighter than 10th visual magnitude. The positions have typical precision in the five astrometric parameters of 1.5 mas for the majority of stars. Lack of precise knowledge of the stars' proper motions will make this catalog degrade in position from epoch 1991.25. This catalog was linked to the ICRF via objects that displayed radio and optical emission. The most precise measurements were obtained of bright Hipparcos stars, which displayed radio emission (Kovalevsky et al. 1997). This uncertainty in the link is 0.6 mas and 0.25 mas/yr in position and time dependent rotational

proper motion parameters. Future VLBA measurements are needed to maintain the accuracy of this link. The Hipparcos catalog is the realization of the optical reference frame of the ICRF.

VII. Implications for Astrophysics

The position of radio and optical emission of celestial objects and the "ICRS" can now be determined to 0.25 and 5 mas respectively at epoch 2000. To accomplish this the "ICRS" must be modified using the IERS Conventions (McCarthy 1996). This can be accomplished by offsets from ICRF or Hipparcos objects. It is difficult to accomplish since the density of ICRF sources is not very great and the error in measurement is directly proportional to the separation of the object from the reference source. At optical wavelengths this is also true as most telescopes have a field of view less than a degree. The Astrographic Catalog Tycho (ACT), a catalog of 10^6 stars, helps this situation substantially but the accuracy of the positions in this catalog is about 40 mas at epoch 2000. Many astrophysical questions may be answered. A sample follows. At radio wavelengths, the parallax of the radio source at the galactic center may be measured directly; its emission at optical/IR wavelengths may be measured using the correlation in position of stars and the optical/IR emission of star forming regions with maser emission; the geometry of the shells of late type stars may also be studied via their maser emission; and stellar radio emission may be identified with particular stars in binary systems. At optical wavelengths, the scale of the universe can be determined to better than 10% via the parallax of nearby standard candle RR Lyraes and Cepheids, galactic kinematics via the study of nearby stars and the evolutionary sequences of stars may be studied in detail.

VIII. Geodesy

VLBI determines the orientation and length of the baseline separating the antennas. Using three appropriately separated antennas such as Green Bank, W Va., Kokee Park, Hawaii, and Fairbanks, Alaska, UT1 and polar motion can be determined precisely, as well as changes in the baseline providing the ability to measure continental drift, given the astrometric accuracy reported for the ICRF. NASA's Crustal Dynamics Project had, as one of its objectives, to develop contemporary descriptions of tectonic motion via space-based geodetic measurements. Satellite Laser Ranging (SLR) and VLBI were developed to provide the data necessary for this. In the case of VLBI, the data are reported as rate of change of baseline length and interpreted as velocities for the stations. Station velocities have been measured with a precision of a mm/yr between the best stations (Westford-Wettzell), with positive detection of motions of a few mm to cm/yr between the North American plate and the Eurasian plate, the Pacific plate, the Australian plate and the African plate (Ryan et al. 1993). This confirmed the NUVEL-1 geologic plate motion model and showed that plate motion is a continuous contemporary process.

The orientation of the Earth as measured by VLBI has led to substantial advances in understanding a number of geophysical phenomena. VLBI measurements of Length of Day (LOD) evolved from a few mas in 1970 to a few tenths of a mas in the early 1990s. Rotational variations have been linked to fluid dynamical processes in the atmosphere, and the LOD has been shown to correlate with changes in the atmospheric momentum. The period of free core nutation has been established and has determined that the Earth's core is not in hydrostatic equilibrium. The models for precession and nutation have been greatly improved. In the future, rotational variations will be used to determine dynamical processes in the atmosphere, oceans

and core and also exchanges in water mass between the atmosphere, oceans and the "solid Earth" (crust and mantle).

Today GPS is evolving to measure precisely geodetic phenomena. The orbits of the satellites now are determined at the 5 cm level by the International GPS Service (IGS). For example, the value of polar motion is based now almost entirely on GPS data. VLBI observations are needed for highly precise measurements on global scales and to validate the GPS measurements.

IX. Summary

In the past thirty years, the technology of radio interferometry has contributed greatly to advances in astrometry and geodesy. Barry has played a leading role in its development and deserves a great deal of thanks for his efforts. The VLA and VLBA will take a leading role in the further development of these fields if a substantial amount of observing time is granted to develop further our understanding of the evolution of the structure of the radio emission in compact extragalactic radio sources as well as obtaining a more complete understanding of the contribution of the atmosphere to errors of astrometric measurements.

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